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DEMAND SPECIFYING VARIABLES AND CURRENT VENTILATION RATE REQUIREMENTS WITH RESPECT TO THE FUTURE USE OF VOC SENSING FOR DCV CONTROL

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ABSTRACT

Demand Controlled Ventilation (DCV) is a well established principle to provide a certain indoor environmental quality, defined both in the terms of air quality and thermal comfort. This is accomplished by adjusting the supplied airflow rate according to a certain demand indicator, which conventionally has been the temperature or the CO_2-concentration. When compared to schedule driven ventilation, application of DCV can lead to substantial energy savings. However, CO_2 is the pollutant related to human occupancy and it does not provide any indication of so called building-related pollution. Building itself as well as its furnishing and equipment together with different human activities happening in them, are significant sources of different chemicals that may aggravate comfort and in some cases even negatively affect the health of the occupants. That is why emissions of those compounds should be also taken into account in the ventilation control. Recent development in gas sensing technology resulted in a new generation of relatively cheap and practically applicable sensors that can offer measurements of some of the pollutants mentioned above – mainly Volatile Organic Compounds (VOC). This seems to bring a new dimension into the control of DCV systems. This paper is a contribution to the workshop on utilization of VOC sensing technology used for DCV control. The aim of the paper is to provide a short review of different types of demand variables used to control DCV systems and summarize ventilation rate requirements contained in current standards and guidelines with respect to the future potential of VOC sensing.

KEYWORDS
Demand Controlled Ventilation, Volatile Organic Compounds, ventilation rate, air quality

INTRODUCTION

Demand Controlled Ventilation (DCV) is a well established principle to provide a certain indoor environmental quality, defined both in the terms of air quality and thermal comfort. This is accomplished by adjusting the supplied airflow rate according to a certain demand indicator, which conventionally has been the temperature or the CO_2-concentration. When compared to schedule driven ventilation, application of DCV can lead to substantial energy savings [1]. The main principle of DCV is that the building is ventilated only in the case that there is an appropriate need for that. In periods of time, where need for fresh outdoor air is low, the amount of supplied air is substantially decreased. However, DCV is not suitable for all types of buildings, since several conditions need to be fulfilled to select DCV. DCV is suitable for buildings with unpredictable variation of occupancy and buildings where heating or cooling is required during all year. DCV is most effective in buildings, which are characterized by well defined dominant pollutant and, at the same time, have low emission of other non-dominant or non-occupant related pollutants. Human body odours, so called human bioeffluents are considered as a dominant pollutant in non-industrial premises like offices, residences, schools or public buildings. It is a state-of-the-art of DCV systems to use the concentration of carbon dioxide (CO_2) as an indicator of the demand for fresh outdoor air. However, not only human bioeffluents are polluting the air in today's buildings. Buildings themselves as well as their furnishing and equipment together with different human activities happening in them, are significant sources of different chemicals that may aggravate comfort and in some cases even negatively affect the health of the occupants. Emissions of those compounds will not be detected by a CO2 sensor and thus the ventilation rate will not be adjusted to dilute them. Recent development in gas sensing technology resulted in a new generation of relatively cheap and practically applicable sensors that can offer measurements of some of the pollutants mentioned above – mainly Volatile Organic Compounds (VOC). This seems to bring a new dimension into the control of DCV systems. This paper is a contribution to the workshop on utilization of VOC sensing technology used for DCV control. The aim of the paper is to provide a short review of different types of demand variables used to control DCV systems and summarize ventilation rate requirements contained in current standards and guidelines with respect to the future potential of VOC sensing.

DCV STRATEGIES – DEMAND INDICATING PARAMETERS

Currently three main parameters are used to control DCV systems. Those are occupancy, indoor air humidity and the concentration of carbon dioxide (CO_2) indoors. Temperature can also be considered as one of the main demand indicators; however, due to the need to decrease energy consumption it becomes a general trend to separate climate conditioning and ventilation. Therefore this option will not be further considered in the present paper. As the goal of ventilation is to provide fresh outdoor air to ensure health and comfort of the occupants, the role of all the above mentioned parameters is to give an estimate of the air flow, needed to meet the goal.

Occupancy detection

The simplest solution to optimize outdoor airflow according to the current demand is to use the occupancy as the control variable. Occupancy is indirectly related to air quality, as people are important sources of odorous gases, so called human bioeffluents. Occupancy sensors are relatively cheap and represent an effective solution in spaces with rather steady occupation patterns [2]. In some cases, utilization of occupancy sensors together with sensors for relative humidity can be beneficial, because of the poor short term correlation between real concentrations of pollutants and the presence of people [3].

Humidity of the air

Measurement of air humidity is an attractive way of the demand specification for residential buildings. Moisture is generated not only by the occupants of apartments and houses, but also by their activities (showering, cooking, drying clothes, etc.). In the work of ECBCS Annex 18 is moisture considered a dominant pollutant in residential settings [4]. Absolute humidity tends to correlate with the CO2 concentration, and thus with the concentration of occupant related pollution in the space, much better than relative humidity. Therefore it is recommended to use absolute humidity as a control variable. Another factor that has to be taken into account in humidity control is the effect of hygroscopic buffering in building constructions. Humidity levels indoors tend to have less fluctuation when indoor materials have high ability to absorb moisture. Aspects of hygroscopic buffering were investigated as part of the IEA Annex 41[5]. The study of Mortensen et al. [6] showed the importance of accounting also for the water content of the outside air. Its seasonal increase can lead to higher indoor relative humidity levels. If the DCV controller works with a fixed set point this leads to unnecessarily high airflow rates.

Carbon Dioxide - CO_2

Most of the current sensor based DCV systems use CO_2 concentration as the control input. CO_2 is a good indicator of human occupancy and can also be used, to some extent, as an indicator of the emission of VOCs or particulate matter related to human activities (using photo copiers, printers etc.) [2]). Use of CO_2 as a control variable is only appropriate at sufficiently high levels of occupancy, which has unpredictable variation patterns [2, 7].

It is important to note that CO_2 is not an indicator of perceived air quality *per se*, as it gives no indication of the emission of pollutants not related to the occupants (emitted from building materials, furniture, etc.). Moreover, building ventilation also needs to take into account pollutants that are not sensory irritants and thus cannot be identified by human perception, but they may be a risk for human health - radon, CO or NO_x.

Measurement of VOC and other chemicals

An obvious step towards better control of DCV seems to be utilization of sensors that can detect not only CO2 to account for pollution related to occupancy, but also other typical indoor pollutants (VOC, aldehydes, radon). This would give a possibility to account also for background pollution related to the building. Herberger et al. [8] describes the development of a metal oxide semiconductor sensor (MOS) that integrates measurement of human emitted VOCs [9] and several other typical indoor pollutants. The sensor expresses its measurement in so called equivalent CO2 concentration, which is quite similar to the Total Volatile Organic Compound (TVOC) approach [10, 11]. Moreover, another very important possibility for application of chemical sensors could also to use them to warn building occupants in the case of sudden releases of highly toxic pollutants in the space [12].

DEMAND SPECIFICATION

Required ventilation rates from current guidelines and standards

The main aim of ventilation is to exchange indoor air polluted by emissions from various sources like people, their activities, building materials etc. with fresh unpolluted air from outdoors. Primarily, ventilation was rather question of comfort than health, as it was realized that people emit rather smelly more than noxious compounds [13, 14]. This approach to ventilation as a way of eliminating body odours, updated with the task of maintaining thermal comfort was used in standards until the ‘80s. The concentration of CO_2 was used as the primary indicator of human bioeffluents, which was considered as the only problematic pollution source in non-industrial buildings. Fanger and Berg-Munch [15] showed that in a space where humans performing sedentary work were the only pollution source, an outdoor air supply rate of 8 L/s person would lead to about 80% of unadapted visitors to be satisfied with air quality. This leads to an indoor concentration of CO_2 of 660 ppm above outdoors and thus absolute concentration (assuming a CO_2 production rate of 19 L/h person and outdoor levels of CO_2 in the range between 300 and 500 ppm) of about 1000 ppm. This value was recommended already by Pettenkofer (1858) [16] in the 19th century. The requirement of a steady-state CO_2 concentration below 800 ppm above outdoors has been adopted in all current ventilation standards [17, 18, 19, 20].

Later studies showed that occupants were not the only source of pollution in buildings. There are thousands of other compounds than human bioeffluents originating from building materials, office equipment etc. Some of these compounds, like for example formaldehyde or radon [21, 22, 23] can mean significant health threat for people, other can be strong sensory irritants and cause degradation of the perceived air quality [24]. This implies that there is a need to ventilate not only for the pollution load originating from people, but other sources need to be also included.

World Health Organization (WHO) drafted 1983 a document on the possible risks of indoor air quality problems [25]. The publication was later followed by guidelines regarding the most important indoor pollutants [26, 27].

In 1988 Fanger [28] (1988) introduced a method to account not only for human odours, but also for other pollutants that may aggravate perceived air quality (PAQ). This approach to ventilate for “acceptable air quality” was consequently adopted by ventilation standards ASHRAE 62.1 [20] and EN 13779 [19] as well as international ventilation guidelines CEN Report 1752 [17] and European guidelines for ventilation requirements in buildings – ECA [29].

Requirements concerning health have been implemented for well-known noxious pollutants specifying Threshold Limit Values (TLV), which should not be exceeded. Inclusion of building related sources increases the required minimum ventilation rates that are specified based on air quality expressed in terms of percent of dissatisfied occupants (PD) with the PAQ. The typical range of PD is from 10% to 30%. The European guideline ECA [29] established three categories of buildings according to the achieved indoor air quality corresponding to PD values of 10%, 20% and 30%. CEN Report 1752 [17] increased the percentage in the first category to 15%. This division of categories was later adopted by the European standard EN 15251 [18], where also a fourth category for PD > 30% was added. The American standard ASHRAE 62.1 [20] works with a single PD value of 20%.

Table 1 gives an overview of recommended ventilation rates for non-residential buildings where smoking is not allowed according to CEN Report 1752 [17], EN 15 251 [18] and ASHRAE 62.1 [20]. It can be seen that although both the EN and ASHRAE standards use the principle of calculating the total outdoor air flow rate as a combination of the occupant related element (to remove pollution related to human occupancy) and the building related element (to remove pollution related the building) the resulting air flow rates differ significantly. The reason is that the US standard uses the percentage of dissatisfied (PD) of adapted occupants as a criterion for acceptable air quality, whereas both CEN Report 1752 and EN 15 251 use PD of unadapted visitors. As human olfactory senses adapt rather quickly to the sensory pollution load in the room [30], utilization of adapted occupants leads requires less ventilation air to provide the same level of satisfaction.

In addition to the method based on the person and building components, both CEN Report 1752 [17] and EN 15 251 [18] states recommended CO2 concentrations above the outdoor concentration to be used when DCV systems are designed. The recommended values differ slightly in the two standards being: 460 ppm, 660 ppm and 1190 ppm in [17] and 350 ppm, 500 ppm and 800 ppm in [18] for the first three building categories. It is also worth noting that outdoor air flow rates calculated according to these target concentrations do not include the building-related pollution component.

Ventilation requirements can also be set to avoid high levels of relative humidity. This is of special importance in residential buildings where there are, besides people, many other sources of moisture (cooking, washing, drying of clothes or bathing/showering). Relative air humidity levels of 30% to 70% are considered as normal, but the supply air flow rate should be designed so that the relative humidity indoors does not exceed 45%. This value is considered as a limit to prevent growth of house dust mites during winter.

For dwellings, ASHRAE 62.1 [20] recommends ventilation rates for acceptable air quality as a function of the area of the residence and the number of bedrooms. EN 15 251 [18] specifies air change rates per m^2 of the dwelling as well as air flows per person for lining rooms and bedrooms. The largest value expresses the total ventilation rate for the residence. The standard specifies also exhaust air rates for bedrooms and kitchens. These should be adjusted according to the supply flows from the living room and bedrooms.

DISCUSSION

Although many VOC sensors are commercially available, there is no general agreement regarding their suitability for use in indoor air quality applications. Won and Schleibinger [31] conducted a review of commercially available sensors for formaldehyde, radon and VOC. To allow for comparison and to ensure their meaningful use in ventilation systems, the study proposes performance requirements (including selectivity, cross-sensitivity, resolution, response rate, price etc.) for such sensors. For formaldehyde and radon, several sensors meeting the proposed requirements were identified, but no commercial VOC sensors meeting were found. The main drawback factors were: high price for sensor arrays, low resolution (~100 ppb at best vs. ~5 ppb requirement) and the fact that sensors do not measure the concentration of individual chemicals (in the case of photo ionization detector sensors – PID and metal oxide semiconductor sensors – MOS). Due to this drawback, the authors concluded that no VOC commercial sensors were identified that would be sensitive and specific enough to be used for ventilation control. Therefore it seems that sensors measuring VOC may need future development.

Also more field- and laboratory tests seem to be needed to bring the technology to the level where it will be fully comparable with the current state of the art CO_2 based control. The main argument for the adoption of VOC sensors is that they are able to detect also diverse odorous events taking place in the space. This may certainly be an advantage, however the performance of VOC sensors was not, on a long term basis, compared to current CO_2 driven DCV. So far only comparisons to schedule based ventilation are available in the literature [32]. In the future, VOC/chemical sensors can maybe find their use as detectors with particular sensitivity to specific noxious contaminants. Their signal would become a control variable in the case of release of a toxic pollutant, while normal comfort ventilation would be based on for example CO_2 concentration measurement.

Ventilation rates recommended by current standards and guidelines are based on target levels of indoor air quality estimated while assuming emissions of typical indoor pollutants (human bioeffluents, background pollution from building). This so called prescriptive approach is mostly used, because most often no precise information about pollutants in a building is available. It is a simple and practical solution for a design engineer who has no possibility of making qualified judgement of occupants' exposure too different contaminants.

Another way to determine the amount of ventilation air is the so called performance-oriented/performance-based approach. This approach specifies requirements in terms of pollutant concentrations that have to be maintained in a given space and/or limit values of an exposure to a given pollutant – "a dose" that cannot be exceeded [33]. ASHRAE 62.1 [20] includes such design approach and states that contaminants of concern of the design shall be identified in terms of their indoor and outdoor sources and their strength. The standard also provides some concentration guidelines. However regarding concentration of VOCs the guideline states that predicted (or measured) acceptability of air quality of more that 80% of occupants or visitors should be used as an indicator regarding odours, while regarding TVOC concentration no precise guideline value can be given. EN 15 251 [18] does not include the performance-based approach, but another standard EN 13779 [19] deals with this approach providing room mass balance equations (both steady state and time dependent) to calculate the airflow needed to reduce emission of other than human related pollutants. The steady state equations are also mentioned in CR 1752 [17].

The performance oriented approach creates an alternative to the prescriptive approach and opens a possibility for innovative technologies to improve both air quality and energy-efficiency. The study of Mortensen et al. [34] used occupant exposure to pollutants integrated over time as the metric to evaluate the effectiveness and air quality implications of demand controlled ventilation in residences. The study compared indoor air quality at two situations: the exposure to pollutants over a long term (typically used in ventilation standards) and the peak exposures associated with time variations in ventilation rates and pollutant generation (background building-related rate and occupant related rate). The DCV system operated at a low and high air flow rate when the residence was unoccupied and occupied, respectively. The authors used analytical solutions to the continuity equation to determine the ventilation effectiveness and the long-term chronic dose and peak acute exposure Logue et al. [35]. The study showed that the peak changes in pollutant concentration were a significant consequence of the dose based design for DCV system. The authors used acute to chronic ratio [36] as a metric to evaluate the possible effects of short term concentration peaks on the occupants. Formaldehyde with an acute to chronic ratio of 4.7 (1h average) was used as the limiting case. The results of the study showed that it was possible to optimize the DCV air flow rates to reduce the quantity of air used for ventilation without introducing problematic acute conditions as the increase in acute to chronic exposure was well below the acute to chronic exposures of concern derived from health standards.

With current knowledge there is still not enough scientific evidence to say how much fresh outdoor air is needed to ensure a healthy indoor environment. A recent review of the scientific literature on ventilation rates and health [37] showed that higher ventilation rates in offices (up to 25 L/s) are associated with lower prevalence of sick building syndrome symptoms (SBS) while ventilation rates higher than 0.5 1/h in residences are associated with reduced risk of allergy among children in a Nordic climate. The panel of scientists concluded that there is still a substantial lack of knowledge on the effect of climate, outdoor pollution and non-office buildings. The project HealthVent [38] funded by the Executive Agency for Health and Consumers of the European Union (EAHC) represents efforts to develop health-based ventilation guidelines. The project aims to develop such guidelines while reconciling the health of the occupants and low energy use in offices, homes and public buildings such as schools, nurseries and day-care centres.

DCV systems controlled by sensors that are sensitive to one or several well-defined pollutants seems to be an appealing alternative to current, mostly schedule or CO_2 controlled systems. However, building occupants are exposed to hundreds of different chemical compounds and even if some representatives are chosen from a so called “universe” of Organic Compounds in Indoor Air (OCIA) introduced by Wolkoff and Nielsen [39], control of ventilation according to them does not necessarily ensure good indoor air quality. Moreover, the chemical universe in buildings is under constant development. According to Weschler [40], concentrations of several indoor pollutants like formaldehyde or PCB have increased and then decreased again. At the same time, concentrations of other chemicals have increased and still remain high (e.g., phthalate esters or brominated flame-retardants). Despite the fact that the amount of scientific literature on the topic of indoor air quality has increased dramatically during last 20 years [41], we still have little knowledge about the compounds that are the most important ones for “the good indoor air quality”. This means a substantial limitation and thus a huge challenge to the control of ventilation systems by chemical sensors.

CONCLUSIONS

- Occupancy detection, measurement of air humidity (relative or absolute) and measurement of the CO2 concentration or their combinations represent the state-of-the-art of control variables for DCV systems.
- VOC sensing seems to be a promising approach to improve the control of DCV systems. However more research is needed to clarify whether VOC sensors should be used as a complementary feature to current systems or if they can be used as standalone sources of a signal for DCV controllers.
- Current ventilation standards and guidelines apply mostly a prescriptive approach to specify required air flow rates depending on the type of premises, occupancy and level of building related pollution.
- The performance based approach specifying ventilation requirements in terms of limit concentrations for specific pollutants is now part of both US and European standards and can be used to design DCV systems.

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Table 1 – Comparison of recommended ventilation rates for non-residential buildings (non-smoking) according to CR 1752 [17], EN 15 251 [18] and ASHRAE 62.1 [20]

Building type	Occupancy	Category CEN	Category EN	Minimum ventilation rate (occupants=only source of pollution), L/s person		Additional ventilation rate (pollution from building) L/s m2				Total air change rate L/s m2		
				CEN*	ASHRAE	EN Very low-polluting	CEN* Low-polluting	CEN* Not low polluting	ASHRAE	EN Very low-polluting	CEN* Low-polluting	ASHRAE
Single office	0.1	A	I	10	2.5	0.5	1.0	2.0	0.3	1.5	2.0	0.55
		B	II	7		0.3	0.7	1.4		1.0	1.4	
		C	III	4		0.2	0.4	0.8		0.6	0.8	
Landscaped office	0,07	A	I	10	2.5	0.5	1.0	2.0	0.3	1.2	1.7	0.48
		B	II	7		0.3	0.7	1.4		0.8	1.2	
		C	III	4		0.2	0.4	0.8		0.5	0.7	
Conference room	0,5	A	I	10	2.5	0.5	1.0	2.0	0.3	5.5	6	1.55
		B	II	7		0.3	0.7	1.4		3.8	4.2	
		C	III	4		0.2	0.4	0.8		2.2	2.4	
Auditorium	1,5	A	I	10	3.8	0.5	1.0	2.0	0.3	15.5	16	6
		B	II	7		0.3	0.7	1.4		10.8	11.2	
		C	III	4		0.2	0.4	0.8		6.2	6.4	
Cafeteria/restaurant	0,7	A	I	10	3.8	0.5	1.0	2.0	0.9	7.5	8	1.17
		B	II	7		0.3	0.7	1.4		5.2	5.6	
		C	III	4		0.2	0.4	0.8		3.0	3.2	
Classroom	0,5	A	I	10	3.8	0.5	1.0	2.0	0.3	5.5	6	2.2
		B	II	7		0.3	0.7	1.4		3.8	4.2	
		C	III	4		0.2	0.4	0.8		2.2	2.4	
Kindergarten	0,5	A	I	12	5.0	0.5	1.0	2.0	0.9	6.5	7	3.4
		B	II	8.4		0.3	0.7	1.4		4.5	4.9	
		C	III	4.8		0.2	0.4	0.8		2.6	2.8	
Department store	0,15	A	I	14.7	3.8	1	2.0	3.0	0.6	3.1	4.1	1.17
		B	II	10		0.7	1.4	2.1		2.2	2.9	
		C	III	6		0.4	0.8	1.2		1.3	1.7	

*requirements of CEN 1752 [17] and EN 15 251 [18] are equal